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13. ABSTRACT (Maximum 200 words)  Work in several areas of laser cooling and trapping of atoms were done during the granting period. Work in atom manipulation with Raman pulses of light, atom interferometers, atomic fountain frequency standards, a new technique in sub-recoil laser cooling, novel far de-tuned optical dipole traps, polymer experiments with single molecules of DNA are described. The work includes seven Physical Review Letters, two Science articles and a cover article for Science.  DTIC QUALITY INSPECTED 5					
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## I. Technical Summary of the work done under the Grant AFOSR-91-0395

### 1) *Laser Cooling and Trapping of Atoms*

During this granting period, we introduced a number of new techniques to the field.

#### A. Atom manipulation techniques

We were the first group to conceive and demonstrate the launching of atoms in an atomic fountain with "moving molasses", a technique that enables one to accelerate atoms while keeping polarization gradient temperatures.<sup>1</sup> We reported a preliminary measurement of the Casimir force between an atom and a surface by reflecting an atom (with nanokelvin energy normal to the surface) from a repulsive potential created by an evanescent light field.<sup>2</sup>

#### B. Raman Pulses for Atom manipulation

Two papers introduced the use of stimulated Raman pulses to manipulate atoms. Raman pulses were first used to velocity select a very narrow velocity class of atoms ( $T_{\text{eff}} = 24 \times 10^{-12}$  K) just before the previous granting period. In this first paper, we also showed how to measure very narrow velocity distributions that could not be measured by ballistic techniques. During the past granting period, we made a theoretical analysis of the effects of the Raman transitions by generalizing earlier work to the off-resonant case and incorporating the mechanical effects of the transitions on the atoms.<sup>3</sup> The advantage of using Raman transitions to manipulate atoms are (1) the transitions are between ground states, so that the long atomic fountain times will not be limited by the lifetime of the excited states, (2) the Raman lasers only require a differential frequency stability (which can be made to be less than a milli-hertz) so that long measurement times can be used, and (3) the Doppler effects are twice as large as the case for a single photon transition.

#### C. Atom Interferometers

Using stimulated Raman  $\pi/2$  pulses between ground atomic states as beamsplitters and  $\pi$  pulses as mirrors, a novel interferometer based on a  $\pi/2$ - $\pi$ - $\pi/2$  pulse sequence and using slow atoms in an atomic fountain was constructed.<sup>4,5,6</sup> This interferometer was one of four interferometers reported within a three month period. What distinguishes this device from the others is that our interferometer remains the only precision instrument. In our first publication, we reported the measurement of the acceleration of an atom due to gravity to a precision of a few parts in  $10^6$ . We followed up the first work with longer paper which

gives a more detailed theoretical analysis of the interferometer and a new experimental measurement where the resolution of  $g$  was improved to  $\Delta g/g = 3 \times 10^{-8}$ .<sup>7</sup>

With a four  $\pi/2$  pulse atom interferometer (first used by Helmecke and collaborators to observe rotation), we measured  $h/M_{Cs}$ , where  $h$  is Planck's constant and  $M_{Cs}$  is the mass of the cesium atom.<sup>8,9,10,11</sup> In this work, we measured a fundamental constant with an absolute accuracy of one part in  $10^6$ . With another two order of magnitude increase in the accuracy of this experiment and a separate measurement of the mass ratio of  $m_e/M_{Cs}$  the value of the fine structure constant can be improved.

Most recently, we have been working towards the goal of improving the precision of atom interferometry to the part per billion level, six orders of magnitude better than the work of other researchers in the field. A crucial element is the construction of a novel low frequency vibration isolation platform in the range of 0.02 to 50 Hz. A first, prototype system has been built and tested in the latest version of our interferometer. With the new isolation system, the free fall time of our atom interferometer/atomic fountain has been extended to 0.25 seconds with only a 25% loss in fringe contrast.<sup>12</sup>

A second important advance in atom interferometry was the first use of adiabatic population transfer to make an atom interferometer.<sup>13</sup> Adiabatic population transfer, as first introduced by Bergmann and colleagues, provides a method of transferring atomic population from one quantum state to another with a method that requires less fine tuning than our original Raman method. We demonstrated an efficiency in the population transfer of 98.5% efficiency per  $2\hbar k$  for Doppler free transitions and over 95% for Doppler sensitive transitions. As many as 200 photon momenta were coherently transferred in our work. In addition, we proved that this method will not cause an AC Stark shift during the transition for a pure three level system, even if the process is partially non-adiabatic.<sup>14</sup>

#### D. Atomic Frequency Standards

A large magneto-optic trap in a vapor cell was constructed where over  $4 \times 10^{10}$  atoms were trapped at a density on the order of  $10^{11}$  atoms/cm<sup>3</sup>.<sup>15</sup> The optical density of the atoms in this trap has a peak attenuation of  $e^{-175}$ . This apparatus was then used to make the first frequency standard based on an atomic fountain of cesium atoms.<sup>16</sup> Earlier work such as our original atomic fountain [ M.Kasevich, *et al.*, Phys. Rev. Lett. **63**, 612, (1989) ] and the French effort [ Audion, *et al.* Europhys. Lett. **16**, 165, (1991) ], can not be considered to be frequency standards since the magnetic fields were not adequately controlled.

Our cesium fountain currently has a short term stability of  $\sim 3 \times 10^{-13}/\tau^{1/2}$ , roughly an order of magnitude better than the PTB frequency standard. In a review article, we examined the prospects for slow atom frequency standards.<sup>17</sup> Most of the systematic effects that limit the current accuracy of today's frequency standards decrease as the velocity of the atoms is reduced. One possible exception are collisions between ultra-cold atoms.

We measured the phase shift due to collisions between 2  $\mu$ K atoms in the atomic

fountain.<sup>13</sup> The measured phase shift was larger than predicted by Verhaar and collaborators, but since the relative density could be accurately measured, an extrapolation of our measurements to zero density had an uncertainty of  $3 \times 10^{-14}$ . Based on our results, we feel that the absolute accuracy of an atomic clock based on a cesium fountain can approach  $\Delta\nu/\nu = 10^{-16}$ .

We went on to interpret the measured collisional frequency shifts using supplied channeled theory and a simple model of hyperfine coupled long range molecular states.<sup>18</sup> With this simple model we can extract the *sign* of the s-wave quantum mechanical scattering length. These results are important in attempts to realize Bose condensation in ultra-cold atomic cesium vapor.

#### E. Raman Cooling

We introduced a new method of cooling below the recoil temperature  $k_B T = (\hbar k)^2 / 2M$ , and obtained one dimensional effective temperature more than an order of magnitude below the recoil temperature (100 nano-kelvin) with sodium atoms.<sup>19</sup> The velocity phase space build-up near  $v=0$  was over a factor of 8. The method was generalized to 2 and 3 dimensions.<sup>20</sup>

#### F. Optical dipole traps

A blue de-tuned dipole trap for sodium atoms was demonstrated. Using 514 nm and 488 nm light from an argon laser, a "boat"- shaped trap that used both gravity and the repulsive force of the light to fashion the trap.<sup>21</sup> The storage time of the trap was 4 seconds and more importantly, the quantum coherence of the atoms in the two hyperfine states was shown to exceed 4 seconds, an order of magnitude longer than the free fall time in an atomic fountain. In a dipole trap made with light from two crossed, focused beams from a YAG laser at  $1.06 \mu\text{m}$ , atoms were trapped for a similar amount of time and evaporatively cooled to temperatures such that  $v_{\text{rms}}$  was less than the photon recoil velocity  $v_r = \hbar k / M$ .<sup>22</sup>

A number of review articles, articles for the general physics audience, and two summer school lectures series were written.<sup>23,24,25,26,27,28,29</sup> Two encyclopedia articles were written including a 17,000 word article for the Encyclopedia Britannica.<sup>30,31</sup>

#### 2) *Polymer and biophysics at the single molecular level.*

The technique we developed to manipulate single molecules of DNA with lasers has been applied to polymer physics and bio-physics. Preliminary elasticity measurements of single molecules of DNA made possible with the optical manipulation of DNA with optical

tweezers was published.<sup>19</sup>

Our first complete experiments were published as a cover article in Science. The first paper described the observation of reptation of a single molecule in a polymer melt by optical microscopy.<sup>32</sup> The paper provides direct and graphic confirmation of the reptation model of polymer diffusion in a field of entangled polymers first proposed by de Gennes, Edwards and Doi in 1971. The second paper measured the relaxation of a single DNA molecule in solution as the first test of dynamical scaling far from equilibrium. The DNA was stained with a fluorescent dye and its end-to-end length was measured as a function of polymer length.<sup>33</sup>

A third paper measured the stretching of a single tethered polymer in uniform flow and showed that the molecule is not free draining, even near full extension.<sup>34</sup> This result is in disagreement with the "blob" model developed by de Gennes and Bouchard.

We are also continuing to develop techniques to examine and quantitatively measure biological function at the single molecule level. The program, in collaboration with Prof. James Spudich of the Biochemistry Department, is studying the force generated by a myosin molecule on an actin filament.<sup>35,36</sup> We also have begun a program to study the motion of enzymes such as RNA polymerase and exonuclease along DNA, but do not yet have results.

## **II. Talks (from 9-1-91 to 12-30-93 only)**

Many invited talks have been given at universities and conferences. The invited talks include two series of 3 lectures at the Enrico Fermi Summer School, Varenna, Italy, in 1991 and 1992; the Public Lecture of the Australian Academy of Sciences; the Australian Optical Soc. Meeting; an after dinner speech at the ILS Symposium in Monterey; the AIP Industrial Affiliates Meeting; the Optical Soc. General Meeting; the Pew Lecture at Pomona College; AT&T Bell Laboratories General Physics Colloquium; the Aspen Winter Conf.; Distinguished Lecture Series at Texas A&M (3 lectures); the Maria Gelpert Meyer Lecture at UC San Diego; the NIH Muscle and Motility Conference; the National Academy of Sciences "Symposium on the Frontiers of Science"; QELS '92; IQEC '92; the Atomic Beams Conference '92; a plenary talk at the AAAS Meeting '92; ICAP; the Polymer Physics Gordon Conference; the "Philadelphia Colloquia", a set of two talks sponsored by colleges and universities in the greater Philadelphia area; the Moriond Conference '93; a set of lectures in Saudi Arabia as part of the King Faisal International Prize for Science; IRIS Workshop in Tsukuba, Japan; QELS '93; and the 11th Int. Laser Spectroscopy Conf (ELICOLS), plenary talks at LT-20 and the Int Conf. on Luminescence, and the Quantum Optics Conf. of the European Phys. Soc.

Colloquia were given at Cal Tech; CSIRO; Melbourne Univ.; Univ. of Canberra;

Macquarie Univ.; Univ. of Connecticut; Univ. of Texas at Austin; UC Berkeley; Princeton; Beckman Laser Center, Irvine; Lockheed; Lawrence Livermore Labs, Univ. of Colorado; Univ. of Chicago; Univ. of Michigan; Stanford in the Chemistry, Chemical Engineering, Mechanical Engineering, Geophysics Departments, SLAC, and Biophysics; Amherst College; and the Univ. of Wisconsin. In addition to these talks, numerous invited and contributed talks have been given by various members of the group.

### **III. Patents**

A patent with C. Wieman and W. Swann has been awarded for "An improved frequency standard using an atomic fountain of optically trapped atoms". Another patent application for "method and apparatus for optically manipulating microscopic particles" (co-inventor S. Kron) for the DNA work has been awarded. Three patents have been filed with M. Kasevich on Raman light-pulse atom interferometers: two patents have been awarded so far. A patent for the acousto-optic control of optical tweezers light beams in an automatic feedback system has been filed. Several other patent disclosures have been filed.

### **IV. Student and Post-doctoral Training**

The first three students have graduated from the Chu group during this period. Mark Kasevich is currently an assistant professor at Stanford. Mark Kasevich has won the American Physical Society prize for the best Ph.D. thesis in 1992 in AMO physics and a recipient of a NSF-PYI award. Mike Fee is now a researcher in the basic research area of AT&T Bell Laboratories. David Weiss went on as an NSF post-doc working with Serge Haroche in France, and is one of five finalists for the APS prize that Kasevich won in 1993. He is currently an Assistant Professor in the Physics Department at Berkeley.

Eight undergraduate students spent at least one summer in the Chu lab during this granting period. Four have graduated and continued their education in physics at Berkeley (Tom Lee and Balazs Kralik), and Oxford (Steve Quake) and in EE at Stanford (Gregg Tsujimoto). Balazs Kralik won the Dean's award for Academic Achievement while Steve Quake is a Marshall Scholar, Firestone Award winner (for outstanding research for an undergraduate at Stanford), and the 1991 Apker Award winner for the best physics undergraduate thesis in the United States. Chris Niell has won the Firestone award for 1995, and will take one year off to teach at the Menlo School and do research in my lab. Dolores Bozovic and Anita Goel are continuing their studies at Harvard in physics and the MD-Ph.D. program respectively.

Post-doc Kurt Gibble began as an assistant professor at Yale in Sept. 1993. Erling Riis is now an assistant professor at the University of Strathclyde. Martin Weitz has a staff position at the Max Planck Institute in Garching Germany, Nir Davidson has a staff position at the Weizmann Institute in Israel. Although not supported by AFOSR funds, four previous post-docs have also done well: Leo Hollberg is a group leader at NIST, Arjun Yodh received early tenure at the University of Penn and Takahiro Kuga is a tenured at the University of Tokyo.

## V. Awards

In recognition of the work sponsored by the AFOSR, S. Chu was named co-winner (with Herbert Walther) of the King Faisal International Prize for Science in 1993. The prize is awarded once every four years in Physics. It includes a \$93,333 cash award and gold medal. The previous winners for Physics were G. Binnig and H. Rohrer, T. Hänsch and A. Zewail.

S. Chu was also named the 1994 winner of the Arthur Schawlow Prize of the American Physical Society and the 1994 recipient of the William F. Meggers Award of the Optical Society of America, and a Distinguished Traveling Lecturer of the American Physical Society laser Science Topical Group for 1994-95. He was elected a Fellow of the American Academy of Arts and Sciences, and to the National Academy of Sciences and the Accademia dei Lincei during the granting period. He was named a winner of the Humboldt Senior Scientist Award for 1995-96.

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